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Modeling of biomass gasification: A review

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ABSTRACT

Biomass is being considered seriously as a source of energy generation worldwide. Among the various routes available for biomass based energy generation, biomass gasification is one of the most important routes that are being studied extensively. Biomass gasification is a thermo-chemical conversion process of biomass materials within a reactor. Number of inter-related parameters concerning the type of fuel, the reactor design and operating parameters effect the functioning of the gasifier. Understanding of this working principle is essential for the end user. The end user may be an individual who is interested in the output of the gasifier or the reactor manufacturer who is interested to develop the most optimum design or a planner who is in requirement of a gasifier which will give the best performance for a specific fuel type. Research and development both in the experimental and computational aspect of gasification has been numerous. Computational modeling tools are advantageous in many situations due to their capability of allowing the user to find the optimum conditions for a given reactor without going in for actual experimentation which is both time consuming and expensive. The modeling works of gasification process requires a systematic logical analysis in order to efficiently disseminate the embedded information. An attempt has been made in this study to categorise the recent modeling works based on certain specific criteria such as type of gasifier, feedstock, modeling considerations and evaluated parameters. Comparative assessments are made of the modeling techniques and output for each category of the models. The information is anticipated to be useful for researchers, end users as well as planners.

Contents

1. Introduction

The world is facing a major energy crisis in the recent years. Alarming increase in climate change and global warming has been attributed to the exploitation of fossil fuels. To cope up with the ever increasing demand for energy and keeping in view the problems associated with fossil fuel utilization, research have been directed towards utilization of alternative sources of energy which will help in fulfilling the energy demand and also to mitigate the environmental problems. In comparison to the conventional sources of energy, which are concentrated in a limited number of countries, renewable energy resources exist over wide geographical areas. Deployment of renewable energy technologies are therefore believed to contribute significantly to energy independence of the region along with associated economic and environmental benefits. In this regard,

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biomass has come up as a major source of alternative energy having widespread availability and comparatively lower environmental impact than fossil fuels.

The major problem associated with the utilization of biomass is its bulkiness and inconvenient form. Most forms of biomass have low energy density in comparison to fossil fuel. For example, energy content of air dried woody biomass is around 12–15 GJ/t whereas for sub-bituminous coal it is around 20–25 GJ/t (low heat values) [1]. Handling, storage and transportation of biomass in its raw form thus becomes more costly in comparison to conventional fuels. Thus, to fruitfully utilise biomass, it becomes necessary to improve its properties which elevate its handling, storage and transportation ability. One such method is to convert solid biomass into liquid or gaseous fuels. This can be achieved via either one of the two ways viz. biochemical and thermochemical conversion. Within the thermochemical route, biomass gasification is a major technology that is being extensively used due to its capability of handling wide range of biomass feedstock. Biomass gasification involves the partial oxidation of solid biomass, in presence of heat, into gaseous or liquid fuels.

Biomass gasification is a complex process involving various chemical reactions, heat and mass transfer processes and pressure changes. Gasification, as a whole, is the conversion of solid or liquid feedstock into useful and convenient gaseous fuel or chemical feedstock that can be burned to release energy or used for production of value-added chemicals [2]. Gasification requires a gasifying agent, viz. air, oxygen or steam, to rearrange the molecular structure of the feedstock to convert it into a useful gaseous fuel having higher hydrogen-to-carbon (H/C) ratio. Depending upon the gasifying medium used the gasifiers are basically classified as oxygen, steam or air blown gasifiers. The gasification process proceeds in four steps viz. drying, pyrolysis, oxidation (combustion) and reduction (char gasification). In a typical gasifier drying occurs at a temperature less than 150 °C, pyrolysis occurs in the temperature range of 150–700 °C, oxidation occurs in the range of 700–1500 °C and reduction occurs in the range of 800–1100 °C [3]. In the drying process the moisture in the fuel evaporates causing a release of steam. In the pyrolysis step the volatile component of the feedstock is vaporised as it is heated. The volatile vapour thus generated is a mixture of mainly hydrogen, carbon monoxide, carbon dioxide, methane, hydrocarbon gases, tar, and water vapour [4]. It is observed that biomass feed stocks tend to have more volatile components (70–86% on a dry basis) than coal (around 30%) [5]. Thus, pyrolysis plays a larger role in biomass gasification than in coal gasification. Pyrolysis also results in the production of tar (a black, viscous and corrosive liquid composed of heavy organic and inorganic molecules) and char (a solid residue mainly containing carbon) [6]. The oxygen supplied to the gasifier reacts with the combustible substances present, resulting in the formation of CO_2 and H_2O, which subsequently undergo reduction upon contact with the char produced from pyrolysis [3]. There is one more combustion reaction occurring inside the gasifier which is the oxidation of hydrogen in the fuel resulting in the production of steam. The reduction reactions occurring inside the gasifier are endothermic in nature and the energy needed for these reactions is practically provided by the oxidation or combustion of char. Reduction yields combustible gases such as hydrogen, carbon monoxide, and methane through a series of reactions, the four major reactions being (a) Water–gas reaction, (b) Boudouard reaction, (c) Shift conversion and (d) Methanation [7]. It is seen that the output gas of the gasification process depends upon the properties of the char that is produced in the pyrolysis step. In general, the reactivity of the char determines the rate of the reduction reaction and thus determines the residence time of the gasification process [8]. Gasification reactivity of chars depends upon many factors, such as pyrolysis temperature, heating rate, inorganic constituents and pyrolysis pressure [3].

Gasifiers are categorised as (a) fixed bed (also known as moving bed), (b) fluidised bed and (c) entrained flow gasifiers depending upon how the gas and fuel contact each other [3]. Depending upon the pressure used the reactors are classified as atmospheric or pressurised reactor. Also, if the reactors are heated by an external source then they are known as allothermal or indirectly heated reactors and if the heat is provided by the partial combustion of feedstock they are known as auto-thermal or directly heated reactors [3].

Performance vis-à-vis end-gas composition of a gasification process is dependent upon the feedstock characteristics, the reactor design and the operating parameters [9]. Feedstock characteristics that have been found to have major influence on the gasification process are moisture content, volatile matter, ash content, char, thermal conductivity, organic constituents and inorganic constituents [9].

Mathematical models become a useful tool in representing the real life situation viz. the gasification process, in pertinence to our discussion, with the help of mathematical equations. This representation of the gasification process in mathematical terms helps in gaining an insight about the significance of the operating parameters affecting the gasifier performance. Various studies have been carried out to model the gasification process in order to predict the performance of a biomass gasifier for a given feedstock [10–44]. The gasification models developed are utilised to study the thermochemical processes occurring during the gasification of the feedstock and to evaluate the influence of the operating parameters, such as moisture content, air/fuel ratio, producer-gas composition and the calorific value of the producer gas [10–44]. A comparative study of the developed models is imperative to know their applicability and limitations in order to predict their use in studying a given gasifier design utilizing a given feedstock. This paper attempts to review and compare some of such biomass gasification models studied by different authors.

2. Biomass gasification modeling

Feed stock flow rate, gasifying agent flow rate, equivalence ratio, reactor pressure and reactor temperature are some of the important operating parameters which influence the gasification process greatly [2]. Change in any of the parameter has considerable effect on the end-gas composition and hence on the performance of the gasifier [2]. Also, different feedstock has inherent heterogeneity in terms of their composition and thermo-chemical properties [45]. It is also observed that the parameters affecting the gasification process exhibit an interrelated behaviour [46]. Thus, experimentation to find the optimum conditions for a given reactor design utilizing a certain feedstock becomes time consuming and expensive. Under such conditions, mathematical modeling has been found to serve as an important tool to study the gasifier behaviour in order to optimize its design and operation without going for physical experimentation [10–44]. Mathematical models are developed to give a good representation of the chemical and physical phenomena occurring inside the reactor of a gasifier [2]. Reactor environment inside a gasification system varies at each point in space and time. Statuses at any point within the reactor are going to vary due to dynamic changes in the variables affecting the processes occurring inside the reactor. The major variables within the reactor are pressure, temperature, velocity of flow, density and concentration of each species [7]. These variables are interdependent and have dynamic variability. Chemical reaction, fluid flow, molecular transport and radiation result in the change of these properties at any point [7]. It is noteworthy that the predictive ability of a mathematical model of the gasification process solely depends upon the capability of the model to

represent these variables as realistically as possible. The modeller while developing the model may be tempted to ignore some of the variables or to make a simplifying assumption in order to truncate the complexity of the model. This causes errors in the model results. Thus, utmost care has to be taken in formulating the model so as to minimise the errors in the results. An example in this regard is the Babu and Seth's equilibrium model which incorporated the variation of char reactivity factor (CRF) along the reduction zone of the downdraft biomass gasifier. In the study it was found that exponentially varying CRF along the length was found to have better agreement with experimental results in comparison to the linearly varying CRF [11]. Though it is imperative to make assumptions during the formulation of a model, but resorting to over-simplifying assumptions may cause large errors in the results.

Nevertheless, mathematical models have been found to be effective in providing qualitative guidance on the effect of design, operating and feedstock parameters on the gasifier performance [2]. Due to the inherent complexity of biomass gasification processes, modeling for simulation and prediction of performance of the processes is still an emerging area of research [8]. Approaches for mathematical modeling of gasification process could be categorised into (i) thermodynamic equilibrium, (ii) kinetic and (iii) artificial neural network (ANN) routes. In the following sections a review of recent work done by various authors using different modeling approaches are being discussed. Each modelling approach has been discussed by giving an introduction to the approach followed by key results from different studies. The studies have been are arranged based on the year of publication (in ascending order), the model considerations, the feedstock used and the parameters studied.

2.1. Thermodynamic equilibrium models

A thermodynamic equilibrium model is used to predict the composition of the product gas based on the assumption that the reactants react in a fully mixed condition for an infinite period of time [2]. Equilibrium models are further categorised as stoichiometric models and non-stoichiometric models. Stoichiometric models are based on equilibrium constants [12]. In this modeling approach the specific chemical reactions are identified and used for the estimation of end gas composition. In this approach some of the most important reactions are considered while some other reactions are omitted. This results in errors in the prediction of the developed model. This difficulty is overcome by the non-stoichiometric modeling approach which involves minimization of the Gibbs free energy [13]. This process is more complex but it is advantageous because the identification and consideration of the chemical reactions are not needed [2].

Equilibrium models allow a practical description of the gasification process. In particular, the results of its application can highlight the thermodynamic limits and the relations between different gasification parameters and the composition of the flowing out gas. Although the equilibrium models are simple, they can describe gasification processes with good approximation, such as those occurring in downdraft gasifiers. This kind of gasifier usually operates close to equilibrium conditions. Moreover, thermodynamic equilibrium calculations, which are independent of the gasifier design, may be more suitable for process studies on the influence of the most important fuel and process parameters [10]. Although the pure equilibrium approach is relatively easy to implement and converges rapidly it has inherent thermodynamic limitations. This can be illustrated by the fact that thermodynamic equilibrium in not fully attained during relatively low operation temperatures (product gas outlet temperatures range from 750 to 1000 °C) [14]. Thus, the equilibrium approach does not give a true representation of the process during low operation temperatures. Another such example is the inability of the equilibrium models for fluidised bed gasifiers in predicting some of the kinetically and hydro-dynamically controlled phenomena such as unconverted solid carbon and the formation of gaseous hydrocarbons [24].

Nevertheless, equilibrium models have been used successfully by many researchers in modeling the gasification process in downdraft gasifiers. Some of the recent works are listed in Table 1.

As seen from Table 1, these models differ with respect to the feedstock and process variables considered for the model formulation.

Babu and Sheth [11] presented a study in which they predicted the steady state composition and temperature profiles for the reduction zone of a downdraft biomass gasifier. Their model was based on the model developed by Giltrap et al. [12]. Babu and Seth's model incorporated the variation of the char reactivity factor (CRF) along the reduction zone of the downdraft biomass gasifier. It was observed that the char reactivity factor is the key parameter in modeling the downdraft gasifier, and it directly represents the reactivity of the char in the reduction zone. Appropriate pattern of CRF were investigated along the length of the reduction zone, through modeling, which were then verified with experimental results. However, an exponentially varying CRF along the length was found to have better agreement with experimental results. Thus, it may be suggested that in developing equilibrium models for downdraft gasifiers, consideration of variation of CRF results in better predictive ability of the models. Also, consideration of exponentially varying CRF yields better result in comparison to linear variation.

Melgar et al. [15] developed an interesting approach in formulation of equilibrium models for downdraft gasifiers. They considered the laws of conservation of energy in an open system, the chemical laws of conservation of atomic species and the laws of chemical equilibrium and combined them in order to predict the final composition of the producer gas as well as the reaction temperature. The developed model was validated with experimental results and then the influence of the moisture content and the gasifying relative fuel/air ratio on the producer gas composition and the process

Table 1
Equilibrium model in the study of downdraft gasifiers.

Sl. no.	Author(s) (year)	Feedstock used/molecular formula	Parameters studied
1	Babu and Sheth (2006)	$CH_{3.03}O_{1.17}$	Char reactivity factor
2	Melgar et al. (2007)	Rubber wood	Air fuel ratio and moisture content
3	Gao and Li (2008)	$CH_{3.03}O_{1.17}$	Temperature of the pyrolysis zone
4	Sharma (2008)	Douglas fir bark	Moisture content, pressure, equivalence ratio in gasifier, initial temperature in reduction zone
5	Barman et al. (2012)	$CH_{1.54}O_{0.62\ 2}N_{0.0017}$	Air fuel ratio, mole of moisture per mole of biomass
6	Azzone et al. (2012)	Corn stalks, sunflower stalks and Rapeseed straw	Pressure, temperature, biomass humidity and oxidant agent composition
7	Antonopoulos et al. (2012)	Olive wood, Miscanthus and Cardoon	Reactor temperature, feedstock moisture content

characteristics were studied for different biomasses with defined ultimate composition and moisture content. The ease of implementation and predictive accuracy of the model makes it a good mathematical model. It may be commented that the combination of thermal and chemical equilibrium conditions is advantageous in developing equilibrium models.

As we have already discussed that the gasification process proceeds in a series of steps occurring inside the gasifier. The most important step having critical influence on the end composition is pyrolysis. It is observed that the more detailed the pyrolysis step is, the better is the prediction of the model [16]. While modeling the pyrolysis step it becomes essential to describe the temperature of the pyrolysis zone. Gao and Li [17] undertook one such study to simulate the behaviour of a fixed bed biomass gasification reactor to study the effect of a continuously increasing heating rate and fixed temperature of the pyrolysis zone on the end gas composition in the reduction zone. In the study both the pyrolysis zone and the reduction zone were modelled together. It was observed that for a continuous heating rate of the pyrolysis zone, the concentrations of hydrogen and carbon monoxide increased while those of nitrogen and carbon dioxide decreased with increasing reaction temperature. The methane content increased during the reaction time and at the end of the reaction the concentration decreased. Similar observations were made for water fraction. For a constant pyrolysis temperature, nitrogen and carbon dioxide decreased and methane, hydrogen, carbon monoxide and water content increased with reaction time. In both the modes, the trends of temperature profile and species concentrations were found to be very different. Thus, it is observed that while modeling the pyrolysis and reduction zones together, the temperature profile of the pyrolysis zone has significant effect on the gas composition in the reduction zone. Accordingly, one must take utmost care in modeling the pyrolysis zone in terms of its parameters. In this regard the temperature of the pyrolysis zone is one of the most important parameter having significant influence on the gas composition.

Also, proper mathematical representation of the reduction zone is also critical as chemical reactions among the hydrocarbons in fuel, steam, carbon dioxide, oxygen, and hydrogen in the reactor, as well as chemical reactions among the evolved gases occur in this zone. Of these the char gasification reactions has been found to be the most important. Sharma [18] proposed a full equilibrium model of the global reduction reactions involving char–gas and gas–gas interactions for a downdraft biomass gasifier in order to predict the accurate distribution of various gas species, unconverted char and reaction temperature. The proposed equilibrium model for the reduction zone was able to predict full equilibrium composition and equilibrium constants precisely. It is observed that consideration of a representative char bed length and initial temperature of the reduction zone helps in improving the predictive ability of the model.

Consideration of the uncertainty concerning composition and quality of tar is a difficult issue of gasification modeling. Barman et al. [19] tried to develop a model for a downdraft fixed bed biomass gasifier taking into consideration representative tar composition as input parameter in the model. This study showed successfully that, if the tar mass was accounted for in the mass balance, the rest of the gasification product (permanent gas species, including moisture vapour) may be predicted with considerable degree of accuracy by simple equilibrium model, considered with deviation from the equilibrium for the methane reaction.

Biomass gasifiers have been reported to utilize agricultural residues and municipal wastes in addition to woody biomass for gas generation. Azzone et al. [20] developed an equilibrium model for the simulation of thermochemical gasification and application to agricultural residues. The model behaviour was analysed by varying process parameters (pressure, temperature), biomass humidity and oxidant agent composition. By increasing the pressure in the gasifier, the methane fraction increased. This was due to the fact that the equilibrium constant is inversely proportional to the process pressure. The model, however, overvalued the quantity of hydrogen and underestimated the production of methane. This was attributed to the typical behaviour of the equilibrium model. It was commented that this behaviour could be explained by considering that the methane generated in the low temperature zone could bypass the reaction zone and avoid its reduction.

Equilibrium modeling for downdraft gasifiers has been found to be very useful in predicting the behaviours of downdraft gasifiers. It is because in downdraft gasifiers both pyrolysis and gasification products are forced through the hottest zone (oxidation zone) so that equilibrium is established after a relatively brief time period [18]. In most of the studies discussed above, the effect of reactor temperature and moisture content of the feedstock in a downdraft gasifier were evaluated using the equilibrium models [11,17,20,21,22]. It was observed that H_2 and CO_2 concentrations decreased by the increase in temperature while the concentration of CO increased in high temperatures [17,22]. By increasing process temperature the syngas LHV was found to decrease. This behaviour was attributed to the fact that the combustion process proceeded further in order to increase the process temperature [23]. Moisture content was found to reduce CO fraction in syngas significantly, thus reducing HHV of the gas [22,23].

In addition to its use in studying downdraft gasifiers, equilibrium models have also been used extensively to study the performance of fluidised bed gasifiers (Table 2). In fluidised bed gasifiers the bed particles are kept in a state of suspension by blowing a gasifying agent through the bed of solid particles at a high velocity. This helps in instantaneous heating of the fuel particles which are introduced at the bottom of the reactor because the fuel particles mix quickly with the bed material. This results in a very fast rate of drying and pyrolysis. The resultant product is a component mix with a relatively large amount of gaseous materials. Further gasification and tar-conversion reactions occur in the gas phase. Char is carried away with the gas. In order to minimise this internal cyclone is used.

Depending upon the fluidisation technique the reactors are classified as either bubbling fluidised bed or circulating fluidised bed. Oxygen and steam are basically used as the gasifying agent and depending upon the pressure of the gasifying agent the reactors are classified as atmospheric or pressurised reactors.

Equilibrium models for fluidised bed gasifiers fail to predict some of the kinetically and hydro-dynamically controlled phenomena such as unconverted solid carbon and the formation of gaseous hydrocarbons [24]. In order to overcome these problems, the equilibrium models are usually adjusted using empirical parameters or correlations to match measured data from the gasification reactors. Equilibrium modeling in studying fluidised bed gasifiers are based on either one dimensional or three dimensional stoichiometric equilibrium approach [25–29] or Gibbs free energy minimisation approach [24,30]. Fluidised beds exhibit very complex hydrodynamics due to the non-linear interactions between the two independent media with their own individual movement tendencies—the particles and the fluid [26]. Accordingly, the models are based on two phase theory of fluidisation.

The key parameters influencing the performance of a fluidised bed gasifier are temperature of reactor, average temperature of incoming bed material, equivalence ratio, moisture content of feedstock, steam to feedstock ratio in case of steam blown gasification and feedstock particle size [26]. Equilibrium models have been used to study the effect of these parameters on the

Table 2
Equilibrium model in the study of fluidised bed gasifiers.

Sl. no.	Author(s) (year)	Model considerations	Feedstock used	Parameters studied
1	Doherty et al. (2009)	Based on Gibb's free energy minimisation approach	Hemlock wood	Equivalence ratio, temperature, level of air preheating, biomass moisture and steam injection
2	Kaushal et al. (2011)	One dimensional steady state model	Wood chips	Mixing of devolatilized gas, average temperature of incoming bed material, moisture content of biomass, steam to biomass ratio
3	Gungor (2011)	One-dimensional, isothermal and steady state and the fluid-dynamics are based on the two-phase theory of fluidization. Tar conversion is taken into account in the model	Biomass	Gasifier temperature, bed operational velocity, equivalence ratio, biomass particle size and biomass-to-steam ratio
4	Loha et al. (2011)	Equilibrium model	Rice husk, sugarcane bagasse, rice straw and groundnut shell	Gasification temperature, steam to biomass ratio
5	Hannula and Kurkela (2012)	Equilibrium model using Aspen plus simulation	Crushed wood pellets and forest residues	Heat losses, gasification pressure, steam/oxygen ratios, filtration temperature and reformer conversion levels, reforming temperature and drying percentage
6	Jun Xie et al. (2012)	The model uses an Eulerian method for fluid phase and a discrete particle method for solid phase, which takes particle contact force into account	Pine wood	Reactor temperature, equivalence ratio, steam to biomass ratio
7	Nguyen et al. (2012)	Empirical model including biomass pyrolysis, char–gas reactions and gas-phase reaction	Pine wood chips	Gasification temperature, steam to fuel ratio

gasification process and reasonable agreement has been found with experimental results in most cases. Some key findings are discussed below.

The producer gas composition depends on the thermodynamic behaviour of the reactions which are greatly affected by the temperature. High temperatures improve product formation in endothermic reactions (Boudouard reaction, water–gas reaction, steam-methane reforming reaction) whereas they favour reactants in exothermic reactions (Methanation reaction, CO shift reaction). High bed temperatures result in less char and tar formation and high gas yields due to improved carbon conversion and steam cracking and reforming of tars [26,30]. Thus an increase in reactor temperature results in production of a gas mixture rich in H_2 with small amounts of CH_4 and higher hydrocarbons [25–30].

With an increase in the temperature of the incoming bed material the H_2 concentration in product gas was found to increase while the concentrations of CH_4 and CO_2 decreased [25].

Equivalence ratio (ER) plays an important role in gasification. Equivalence ratio is defined as the ratio of the actual fuel air ratio to the stoichiometric fuel air ratio where the stoichiometric air is the amount of air required for complete combustion of one unit of the fuel. Equivalence ratio for biomass gasification using fluidised bed has been found to vary in the range of 0.10–0.30 [26,28,30]. It was suggested from these studies that too small ER's tend to lower reaction temperature, which does not favour biomass gasification. On the other hand, too large ER's result in consumption of more H_2 and other combustible gases through oxidization reaction causing a decrease in the HHV of the end gas. Thus, ER is found to have two opposing effects and as such there exists an optimum ER for each reactor which is dependent upon the operating parameters and the reactor design [26,28].

Moisture content in the feedstock has been found to have a very deteriorating effect on the quality of the product gas. It is observed that with the increase of the fuel moisture content, the average temperature of the gasifier goes down due to production of H_2O. As a result of the decreasing temperature the reaction rates slow down and eventually result in lower heating value and inferior quality of product gas [25,26].

The steam to biomass ratio has been found to vary depending upon the gasifier temperature. In the study carried out by Gungor [26] it was found that for a gasification temperature of 800 °C, increasing steam to biomass ratio (1–4) increased hydrogen production. On the one hand, the gasifier needed more heat for higher gasification temperature; whereas, steam needed to absorb much more heat to reach in-bed temperature.

It has been found that small biomass particles contribute to large surface area and high heating rate thereby improving H_2 composition. For small particle sizes the pyrolysis process is mainly controlled by reaction kinetics; as the particle size increases, the product gas resultant inside the particle is more difficult to diffuse out and the process is mainly controlled by gas diffusion [26].

Equilibrium models have also been used to study different types of gasifier designs as shown in Table 3.

Baggio et al. [31] conducted an experimental and modeling analysis of a batch gasification pyrolysis reactor with the help of an equilibrium model. The overall agreement between model predictions and experimental results were reasonably satisfactory; in particular the residual solid yield (char) obtained experimentally at 800 °C was very close (in the range −5% to +15%) to the value obtained by the simulation. Considering the gas phase, the agreement was quite good also for CO and CO_2, it was fair for H_2, while it was poor for CH_4. It was commented that the computed compositions were representative only of processes where the residence time was long enough to establish thermodynamic equilibrium conditions.

Deydier et al. [32] developed a mathematical model for the prediction of the influence of the operating parameters of a gasification process composed of a drying and a gasifying section (travelling bed gasifier). The effect of the ratio of mass flow rate of air used for drying to the mass flow rate of incoming biomass and the ratio of the mass flow rate of air for gasification to the mass flow rate of incoming biomass was studied. An optimal value of the ratio of mass flow rate of air used for drying to the mass flow rate of incoming biomass was found to exist and this value corresponded to the complete and exact drying of the biomass. Optimal value of the ratio of the mass flow rate of air for gasification to the mass flow rate of incoming biomass was found to be associated with the exact and complete gasification of solid carbon.

Table 3
Equilibrium model in the study of some specific gasifier designs.

Sl. no.	Author(s) (year)	Type of gasifier studied	Feedstock used	Parameters studied
1	Baggio et al. (2009)	Indirectly heated batch reactor set in an external furnace	Spruce wood	Char yield
2	Deydier et al. (2011)	Travelling bed gasifier	Coal, wood and grass	Air-fuel ratio for drying and gasification
3	Nilsson et al. (2012)	Three-stage system and a stand-alone fluidized bed gasifier	Dried sewage sludge	Equivalence ratio, steam to oxygen ratio, reactor temperature
4	Bhattacharya et al. (2012)	Oxygen blown biomass gasifier followed by a water gas shift reactor for the production of hydrogen	Wood	Equivalence ratio, amount of water injected in the shift reactor for complete conversion of carbon monoxide and percentage of oxygen in the gasifying agent
5	Pirc et al. (2012)	Universal gasifier	Various biomass	Type of wood, amount of wood moisture, outlet temperature of the syngas, oxidant (oxygen or air)

Nilsson et al. [33] developed a model of a new three-stage gasification system and used the model to compare the performance of a three-stage system and a stand-alone fluidized bed gasifier (FBG) using dried sewage sludge (DSS) as fuel. The equivalence ratio (ER), steam to oxygen ratio (SOR) and reactor temperature were the process parameters whose effect on the system was studied. It was found that for a given SOR there was an optimum range of ER within which the cold gas efficiency (CGE) was maximum. As SOR increased, CGE decreased. The Carbon Conversion efficiency increased as reactor temperature increased upto a certain reactor temperature and then remained constant. The results showed that the reforming of tar in the gasifier is not significant for temperatures below 900 °C. When increasing the steam to oxygen ratio the temperature decreased, leading to less reforming of tar and higher tar content in the gas. These results suggested that the addition of steam is not suitable to enhance tar reforming for atmospheric auto-thermal FBG.

Bhattacharya et al. [34] developed a thermodynamic model to evaluate the yield of hydrogen from biomass through gasification in an oxygen-rich environment followed by carbon monoxide shift reaction with the injection of water. Effect of gasifier equivalence ratio, amount of water injected in the shift reactor for complete conversion of carbon monoxide and percentage of oxygen in the gasifying agent were studied using the model. The hydrogen yield was found to be marginally affected by the percentage of oxygen in the gasifying agent. However, was commented that higher the oxygen percentage, less would be the nitrogen in the gas mixture and easier would be the purification process to obtain hydrogen. The energy consumption per unit mass of hydrogen generated was higher or the higher purity of oxygen in the gasifying agent. Also, it was commented that the energy consumption could be reduced with multistaging of the compressor and intercooling between the successive stages.

Pirc et al. [35] developed a model for a theoretical universal biomass gasifier capable of producing different syngas compositions. It was reported that when the syngas consisted of methane, hydrogen and carbon monoxide, the highest net efficiency of the system was achieved. Producing syngas for methanol synthesis was found to be interesting area due to its use in a mobile technique. The lowest net efficiency of gasification was achieved when producing a hydrogen-rich syngas; this was because of water reduction, which was an endothermic reaction. It was sensible to use a hydrogen-rich syngas in fuel-cell systems. Using oxygen as an oxidant was found to be efficient in all cases.

It may be observed that equilibrium models have been successfully utilised in the study of different types of gasifiers. It is also seen that modification of the equilibrium models by incorporating empirical correlations based on experimental studies helps in increasing the accuracy of the models.

2.2. Kinetic model

A kinetic model is used to predict the gas yield and product composition that a gasifier achieves after a finite time (or in a finite volume in a flowing medium) [2]. A kinetic model can predict the profiles of gas composition and temperature inside the gasifier and overall gasifier performance for a given operating condition and gasifier configuration.

Kinetic model takes into consideration both the kinetics of gasification reactions inside the gasifier and the hydrodynamics of the gasifier reactor. This becomes important if the residence time required for complete conversion is long which occurs when the reaction rate is very slow at low reaction temperatures. Thus, kinetic modeling is found to be more suitable and accurate at relatively low operating temperatures compared to equilibrium model.

Kinetic modeling incorporates both reaction kinetics and reactor hydrodynamics. While reaction kinetics involves the knowledge of bed hydrodynamics and mass and energy balances to obtain the yields of gas, tar, and char at a given operating condition, reactor hydrodynamics involves the knowledge of the physical mixing process.

The rate of the char gasification reaction is expressed in terms of the external surface area of the biomass char or in terms of the reactor volume. This is because as the gasification of a biomass particle proceeds there is mass loss which is manifested either through reduction in size with unchanged density or reduction in density with unchanged size. Again, where the reaction is made up of char alone, the reaction rate is based on reactor volume. Accordingly, the char gasification reaction of biomass is studied using the shrinking core model or the shrinking particle model or the volumetric reaction rate model.

Further, based on the reactor hydrodynamics the following types of models, with increasing sophistication and accuracy are used: zero dimensional (stirred tank reactor), one dimensional (plug flow), two dimensional and three dimensional.

The kinetic model is also sensitive to the gas–solid contacting process involved in the gasifier. Based on this process, the model may be divided into moving or fixed bed, fluidized bed and entrained flow.

Kinetic models are accurate and detailed but are computationally intensive. It may be noted that the complexity and dimensions of the model increases with the desired outputs of the model i.e. more detailed analysis of the system involves incorporation of more detailed reaction kinetics and/or reactor hydrodynamics.

Table 4
Kinetic model in the study of specific gasifiers designs.

Sl. no.	Author(s) (year)	Type of gasifier studied	Feedstock used	Process variables
1	Nikoo and Mahinpey (2008)	Fluidized bed gasifier	Pine wood	Reactor temperature, equivalence ratio, steam to biomass ratio and biomass particle size
2	Saravanakumar et al. (2011)	Updraft fixed bed gasifier	Long stick wood	Air-fuel ratio, gasification temperature
3	Gordillo et al. (2011)	Downdraft solar packed bed gasifier	High carbon content feedstock	Gas flow rate, reactor height, reactor temperature
4	Inayat et al. (2012)	Steam gasifier	Oil palm empty fruit bunch	Temperature and steam to biomass ratio

The complexity of the models can however be reduced by making simplifying assumptions within the different chemical reaction classes but the levels of simplification have to be carefully evaluated to make them coherent with the final aim of the model [47]. Nevertheless, many researchers have focused extensively on kinetic models of biomass gasification. Table 4 enlists some recent works based on kinetic modeling for biomass gasification.

Nikoo and Mahinpey [36] developed a comprehensive process model based on reaction kinetics and reactor hydrodynamics for biomass gasification in an atmospheric fluidized bed gasifier using the ASPEN PLUS simulator. After satisfactory validation of the model using experimental values, the effect of reactor temperature, equivalence ratio, steam to biomass ratio and biomass particle size were investigated using the model. Higher temperature was found to improve the gasification process. It increased both the production of hydrogen and the carbon conversion efficiency. Carbon monoxide and methane showed decreasing trends with increasing temperature. Carbon dioxide production and carbon conversion efficiency were found to increase by increasing the ER. Although, hydrogen, carbon monoxide, and methane decreased when ER was increased, increasing steam-to-biomass ratio increased hydrogen and carbon monoxide production and decreased carbon dioxide and carbon conversion efficiency. Particle average size did not show a significant influence on the composition of product gases.

Saravanakumar et al. [23] developed a computational model to evaluate the anticipated performance characteristics of an updraft fixed bed gasifier utilizing long stick wood as the source of fuel. The computational model indicated that all incoming air was consumed in the charcoal combustion region, and that maintaining a specific air/fuel ratio could lead to a poor measure of gasifier performance. Higher combustion temperature was found to enhance the gasification time, but could waste more energy due to energy carried out by the hot exhaust gases. It was commented that air to fuel ratio could be a more useful measure when moisture was present in the lower portion of the bed to maximize/minimize specific gasification products.

Gordillo et al. [37] studied a numerical model of a solar downdraft gasifier, utilizing high carbon content feedstock viz. biomass char (biochar) with steam, based on the systems kinetics with char reactivity factor (CFR) varying exponentially. The model was aimed to calculate the dynamic and steady state profiles while also predicting the temperature and concentration profiles of gas and solid phases, based on the mass and heat balances. The study suggested that downdraft set-up could be a great solution in order to improve the performance of the packed bed and fluidized bed gasifiers with concentrated solar radiation in the upper side of the reactor. The gas produced was found to be high quality syngas, in which the hydrogen was the principal component followed by carbon monoxide; the carbon dioxide yield was small because no combustion was conducted. The system efficiency was reported to be as high as 55% for small steam velocities. The energy conversion efficiency was found to decrease when the steam velocity was increased and when the bed was heated quickly. The model predictions were in very good agreement with the trends found experimentally and reported in the literature. Moreover, varying CRF exponentially was found to improve the representation of the heat transfer throughout the bed.

Inayat et al. [38] reported the results of a parametric study performed using process modeling for hydrogen enriched gas production via steam gasification in the presence of CaO. The model incorporated the reaction kinetics calculations of the steam gasification with in-situ CO_2 capture, as well as mass and energy balances calculations. Temperature and steam/biomass ratio were reported as the most important variables, as the hydrogen concentration in the product gas increased on increasing the value of both variables. Hydrogen efficiency was found to decrease on increasing steam/biomass ratio as more energy was required for additional steam usage despite the increased hydrogen yield. Additionally, it was observed that temperature had a more significant influence on the hydrogen yield compared to the steam/biomass ratio.

Kinetic rate models contain parameters that limit their applicability to different plants. Also, with increasing complexity in the design of the gasifiers, the complexity of the model increases because the models are based on reactor hydrodynamics.

Equilibrium or kinetic models or combination of both have their own advantages and disadvantages. Whereas equilibrium models are simpler in formulation but do not yield satisfactory results for complex reactor designs, the kinetic models are complex in formulation but their predictions are more accurate compared to equilibrium models for complex reactor designs. Computational Fluid Dynamics (CFD) serves as a tool to study the behaviour of a given gasifier design by incorporating the advantages of both models. Artificial Neural Network modeling is also coming up as a useful tool in analysis of biomass based gasifiers.

2.3. CFD and ANN models

CFD models are used to predict distribution of temperature, concentration, and other parameters within the reactor. CFD models are based on solutions of a set of simultaneous equations for conservation of mass, momentum, energy, and species over a discrete region of the gasifier. CFD models are found to be highly accurate in predicting the temperature and gas yield around the reactor if the reactor hydrodynamics are well known. CFD modelling of biomass gasification involves the combination of dense particulate flow and very specific chemistry [39]. These two aspects are very challenging in CFD. For example, the composition of biomass itself is very complex due to its dependence on feedstock, age, geographic location and time of the year. CFD models have been used extensively to study the performance

Table 5
CFD and ANN models in the study of biomass gasifiers.

Sl. no.	Author (s) (year)	Type of gasifier studied	Feedstock used	Model considerations	Parameters studied
1	Gao et al. (2012)	Air cyclone	Sawdust of walnut	Detailed CFD model of a cyclone gasifier. Models of sawdust pyrolysis and combustion of volatiles and char have been added to the standard model	Equivalence ratio, gas composition
2	Jakobs et al. (2012)	Entrained flow gasifier	Ethylene glycol	CFD model. Steady balance equations for mass, momentum and energy are solved using a finite volume solver	Spray quality
3	Janajreh et al. (2013)	Downdraft bioamss gasifier	Woody biomass	The numerical simulation is conducted on a high resolution mesh accounting for the solid and gaseous phases, k–e turbulence, and reacting CFD model	Gas composition, cold gas efficiency, carbon conversion efficiency, reactor temperature
4	Arnavat et al. (2013)	Circulating fluidized bed gasifiers (CFB) and bubbling fluidized bed gasifiers (BFB)	Woody biomass	Feed-forward ANN model	Ash, moisture, biomass composition, equivalence ratio, gasification temperature for CFB and BFB respectively, steam to dry biomass ratio (kg/kg) for BFB only
5	Sreejith et al. (2013)	Fluidised bed gasifier	Wood sawdust	Feed-forward ANN model and equilibrium correction model incorporating tar (aromatic hydrocarbons) and unconverted char	Product gas composition, heating value and thermodynamic efficiencies

characteristics of different types of biomass gasifiers. Table 5 enlists some recent works based on CFD modeling.

Gao et al. [40] developed a detailed CFD model of a cyclone gasifier, based on the Fluent package. Models of sawdust pyrolysis and combustion of volatiles and char were added to the standard model. The model provided information on the gas temperature in the gasifier and the composition of the outlet gas. The effect of equivalence ratio was studied and validated experimentally. For the cyclone gasifier, the carbon conversion was found to vary between 77.0 and 94.2% and the cold gas efficiency varied between 53.6 and 63.0% when equivalence ratio (λ) was varied in the range of 0.23–0.35. The maximum lower heating value of the produced gas was 5.7 MJ/Nm^3 when λ was 0.23–0.26. Models of sawdust pyrolysis and combustion of volatiles and char were added to the standard model. The model was found to under predict the concentrations of CO and CO_2. The predicted gas temperatures and the produced gas concentrations were found to follow the same trend as the experimental ones, and it was suggested that developed numerical model could provide a good reference for the development of biomass gasifier.

Jakobs et al. [41] developed CFD model of a high pressure entrained flow gasifier. Steady balance equations for mass, momentum, energy and several species were solved using a finite volume solver. Atomization quality of twin fluid nozzles as a function of gas velocity and reactor pressure was analysed. The developed and characterized atomizers were used in the atmospheric entrained flow gasifier, to detect the influence of spray quality on gasification process. Sauter Mean Diameter (SMD) of the produced spray was found to be significantly influenced by gas velocity and reactor pressure. Increasing reactor pressure was found to increase the drop diameter whereas increasing gas velocity decreased the SMD. An influence of SMD on gasification process was observed from organic carbon and methane concentration measurements as well as from the radial temperature profiles at various positions along the reactor centerline. The CFD model of high pressure entrained flow gasification of biomass based slurries showed a very pronounced influence of drop size distribution on gasification quality.

Janajreh et al. [42] investigated the conversion efficiency in a small scale, air blown, downdraft gasification system operated using wood. The experimental investigation of the temperature field inside the gasifier was followed by high fidelity numerical simulation using CFD to model the Lagrangian particle coupled evolution. The numerical simulation was conducted on a high resolution mesh accounting for the solid and gaseous phases, $k-\varepsilon$ turbulence, and reacting CFD model. The downdraft gasifier was modelled using the finite volume code coupled with a conjugate heat transfer with the bulk metal separators and insulation. The temperature distribution and the evolution of species were computed and compared with the experimental results and with the ideal equilibrium, zero dimensional case. The average temperature computed using CFD was higher compared to that measured experimentally. The CFD computed cold gas efficiency (CGE) was found to be 19 points less of that calculated for the ideal case. It was commented that due to the complexity of the flow inside the downdraft gasifier, equilibrium modeling could not capture the physics and chemistry inside the downdraft gasifier compared to other types of gasifiers especially those characterized by their high temperatures such as the entrained flow gasifiers. To account for the particle size of the wood, de-volatilization kinetic data for particles of 1 cm length were used to offset the effect of the particle diameter (0.1 mm) modelled using the discrete phase method (DPM) in ANSYS. The corresponding CFD and experimental temperature profiles suggested that this assumption was reasonable.

A more recent approach for simulation of gasifier is the neural network analysis in which the neural network learns by itself from sample experimental data mimicking the working of the human brain and providing some human characteristics in solving the models. Although this method cannot produce an exact analytical solution but it gives numerical result. A neural network may return poor results for data that differ from the original data it was trained with [2]. This happens sometimes when limited data are available to calibrate and evaluate the constants of the model. Thus, one has to be very diligent in applying the ANN approach. One must ensure that he/she has sufficient data in order to formulate the model. This technique has been used with reasonable success to predict gas yield and composition from gasification processes. Some recent works on ANN modeling have been included in Table 5 and discussed below.

Arnavat et al. [43] developed two ANN models; one for circulating fluidized bed gasifiers (CFB) and the other for bubbling fluidized bed gasifiers (BFB). Both models were used to determine the producer gas composition (CO, CO_2, H_2, CH_4) and gas yield. The effect of ash, moisture, carbon, oxygen and hydrogen content of dry biomass, equivalence ratio and gasification temperature were studied for CFB and BFB whereas the effect of steam to dry biomass ratio (kg/kg) was studied for BFB only. The two ANN

models developed for CFB and BFB gasifiers showed the possibility that ANN may offer some contribution to research in the area of biomass gasification modeling. The results obtained by the two ANN's showed high agreement with published experimental data used: very good correlations ($R > 0.98$) in almost all cases and small RMSE. Biomass composition (C, H, O) in CFB represented between 31.7% and 54.1% of the importance on CO, CO_2, H_2 and CH_4 prediction and in BFB between 28.9% and 52.3%. In the case of producer gas yield prediction, in CFB, the ER input was found to be the most important variable (37.6%) while in BFB model it decreased down to 10.8%.

Sreejith et al. [44] developed a feed-forward artificial neural network (ANN) model for the prediction of gasification temperature and product gas composition and a Redlich–Kwong real gas equilibrium correction model incorporating tar (aromatic hydrocarbons) and unconverted char to predict the product gas composition, heating value and thermodynamic efficiencies. Good accuracy of ANN prediction with experimental results was reported which was based on the computed statistical parameters of comparison such as coefficient of correlation, root mean square error (RMSE), average percentage error and covariance. The corrected equilibrium model developed by introducing correction factors for real gas equilibrium constants showed satisfactory agreement (RMSE = 5.96) with the experimental values. Maximum concentration of hydrogen achieved experimentally was 29.1% at the equivalence ratio = 0.277 and steam to biomass ratio (SBR) = 2.53. The corresponding predicted values were 28.2% for ANN model and 31.6% for corrected equilibrium model. The corrected equilibrium model for wood sawdust was validated with major air–steam gasification experimental results of other biomass materials and was found to be 95.1% accurate on average. It was revealed from the study that the ANN model (RMSE = 2.64) was a better predictor for the product gas composition than the corrected real gas equilibrium model (RMSE = 5.96). The study proposed a more comprehensive ANN model capable of simulating various process conditions in fluidised bed gasification applicable to variety of biomass feedstock.

3. Conclusion

Mathematical modeling serves as an important route to study the gasifier behaviour in order to optimize its design and operation in comparison to physical experimentation which is both time consuming and uneconomical. For example, for commissioning a gasifier at a given location if the suggested feedstock is not available then the gasifier has to be run on the different available feedstock and the best among them has to be found. This process becomes both time consuming and expensive. On the other hand, if we have a mathematical model of the system then we can easily find out which feedstock will give the optimum output by studying the output of the model in accordance with the characteristics of the available feedstock. Mathematical models are formulated to give a good representation of the chemical and physical phenomena occurring inside the gasifier. Equilibrium modeling, kinetic modeling and artificial neural network modeling are the approaches that are mostly used in biomass gasification study.

Equilibrium modeling for downdraft gasifiers has been found to be very useful in predicting the behaviours of downdraft gasifiers. This can be attributed to the fact that in downdraft gasifiers both pyrolysis and gasification products are forced through the oxidation zone which has the highest temperature. This enables establishment of equilibrium in a relatively brief time period. Although simple in formulation, equilibrium models have inherent limitations. It is also observed that modification of the equilibrium models by incorporating empirical parameters or correlations based on experimental studies helps in increasing the accuracy of the models.

Kinetic modeling incorporates both reaction kinetics and reactor hydrodynamics. While reaction kinetics involves the knowledge of bed hydrodynamics and mass and energy balances to obtain the yields of gas, tar, and char at a given operating condition, reactor hydrodynamics involves the knowledge of the physical mixing process. Kinetic models are accurate and detailed but are computationally intensive. Kinetic models have the ability to predict the progress and product composition at different positions along a reactor. Kinetic model proves to be a very powerful tool in analysing gasification systems.

CFD has served as an important tool in order to study the behaviour of gasifier design by incorporating the advantages of different models. It may however be noted that studies involving detailed and accurate chemistry of the gasification process combined with detailed numerical methods for multi-phase flow are also essential in order to develop a comprehensive CFD simulation of the gasification process.

Neural Network modeling is also being utilised by some authors as a novel approach in studying biomass gasification. ANN serves as an alternative to the sophisticated modelling of the complex gasification process. Although ANN cannot produce analytical results, it gives numerical results.

The present study reviews the current advances in the field of biomass gasification modeling and categorises them into different heads depending upon certain specific criteria such as type of gasifier, feedstock, modeling considerations and evaluated parameters. Such information will be useful for researchers and planners by serving as a guideline for adopting a suitable modeling approach or for selecting a suitable gasifier for their intended application.

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